SLAC MEMORANDUM

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TO Participants at the **Mini Workshop on Design for High Availability** ,**Dec 1- 2, 2005**

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SUBJECT: Experience in calculating Mean Times Between Failures for magnets and power supplies at SLAC – how much they can vary and how to use them to calculate magnet and power supply availabilities in a linear collider with many thousands of magnets and power supplies.

This memo will provide you with a few "measured" availability data points for electromagnets and magnet power supplies which have been generated from actual SLAC failure data by Seung Rhee of the Stanford University Mechanical Engineering Department and myself. The process we followed in 2002 to generate Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR) is described in the 9 step list below.

I want to assure you that we worked carefully with knowledgeble SLAC staff in extracting magnet and PS failures from the SLAC CATER database of accelerator failures. This staff person made sure he did not miss any magnet or PS failures in the 1997 to 2001 period we had chosen. We inspected in detail all the CATER entries he found and made sure they really were magnet or power supply problems and had not been wrongly categorized. We also scrutinized the reported "Beam Time Lost" for each failure and if it didn't make sense considering the type of failure I went to the operator's logbook on the web and worked out a reasonable time (these times became "time to repair").

Process followed by Rhee and Spencer:
1.Obtain magnet failure history (CATER system) for 5 year period (1997-2001)
2.Categorize data into solid wire and water-cooled electromagnet types.
3.Calculate average beam downtime for different types of magnet from failure data.
4.Obtain SLAC beamlines runtime schedule for this 5 year period.
5.Count number of magnets in each SLAC beamline during specific runtime periods.
6.Identify magnet failures that shut down the beam from CATER system report for each runtime period.
7.Calculate magnet operating hours by multiplying number of magnets by run hours for each period.
8.Calculate MTBF, MTTR and availability of one magnet for each period.
9.Calculate average availability for one magnet using all or some subset of the SLAC beamlines' data.
This process repeated for switching power supply failures over same period.

You can see from the tables of our calculations given below that one can arrive at a wide range of measured MTBF and MTTR values depending on the time frame, which SLAC beamlines are studied, whether the magnets have solid wire coils or water cooled coils (from my in-depth knowledge of the NLC magnets I predict the ILC will have about 30% solid wire magnets) and whether the power supply is a switching style or not. Based on NLC scenarios I suppose the ILC will have only switching PS for its room-temperature magnets, which will be much more numerous than the main linacs' superconducting magnets. In the availability calculation below I use the numbers of NLC magnets as those were well-defined and the ILC beamlines are still under discussion, but they are similar enough.

Here is the definition of availability of a single component:
Availability, A = MTBF/(MTBF+MTTR)

Note that the Mean Time To Repair a failed component has an equal affect on its Availability as its MTBF. Cutting a component's MTTR in half will increase its A as much as doubling its MTBF- and is likely to be easier to achieve. I think we should engineer and design all the accelerator components with minimizing repair time (during which the beams cannot run) as a goal.

Here is a table of the part of our SLAC failure data and calculations that show the wide range of MTBFs and MTTRs for overlapping groups of magnets, i.e. a large fraction of the SLC magnets are also used in PEPII. We have much more data, plus detailed predictions of the costs of all kinds of magnet and PS failures throughout the design, fabrication and 30 year operating life of the NLC, which we could make available to you if you wished. We assumed an all-electromagnet NLC.

Dates line ran	**Beam-line**	**Run Hours**	**No. of Magnets**	**Magnet Hours**	**No. of failures**	**MTBF hours**	**Time to repair**	**MTTR hours**	**Availability of ONE magnet**
5/1/97-6/8/98	SLC	8828	1087 (solid)	9,596,036	0	-	0	0	1
5/1/97-6/8/98	SLC	8828	2302 (water)	20,322,056	32	635,064	469.5	14.67	0.999976898
1/12/00-10/31/00	PEPII	6624	1690 (solid)	10,658,016	3	3,552,672	19.0	6.33	0.999998217
1/10/01-12/31/01	PEPII	7411	2602 (water)	17,235,648	7	2,754,774	37.9	5.41	0.999998035
1/1/02-12/31/02	ALL*	6480	1865 (water) (average No)	12,083,738*	1	12,083,738	3.0	3.0	0.999999752
Dates line ran	**Beam-line**	**Run Hours**	**No. of switching PS**	**PS Hours**	**No. of failures**	**MTBF hours**	**Time to repair hours**	**MTTR hours**	**Availability of ONE sw PS**
2/24/99-5/1/99	Linac	1461	52 (small)	75,972	1	75,972	0.5	0.5	0.9999934
5/1/97-6/8/98	SLC +HER	8828 + 918	85 + 171(large)	907,358	5	181,472	10.3	2.06	0.9999886
1/10/01-12/31/01	PEPII	7411	425 (large)	3,180,835	27	117,809	45.9	1.70	0.9999856

Nomenclature in above table: "solid "= magnets with solid wire coils; "water" = magnets with water cooled coils;
small PS <12A, <50V; large PS >12A,>50V.
"Time to repair" is the total hours the beam was down for the stated failures, so MTTR = Time to repair/No. of failures.
* This 2002 dataset does not include any magnets in the 2 damping rings, which have notoriously failure-prone magnets—by removing them from the dataset one can make the average MTBF vastly longer. We understand why the DR magnets fail more frequently and would avoid making the same design mistakes in ILC magnets.
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Having calculated an availability for a *single* average SLAC accelerator component, one then needs to decide how to apply it to predicting the availability of a system comprised of multiple units of that component in the NLC. One has several choices, one could (a) assume the components couldn't be made to be any more reliable nor could their repair time be decreased and so use the same

availability or (b) the components' reliability could be improved and/or their repair time could be decreased and so a better single item availability could be used for the NLC prediction or (c) some components could have a second, identical, unit placed in service with it and they would be in used in a redundant mode. Redundancy can be used with power supplies but not with magnets.

To start with Rhee and I decided to assume a single NLC magnet will have the same availability as the average single SLAC magnet, so the last step in our process was to predict the availability of the system of NLC magnets by raising the availability of an individual magnet to the power of the total number of magnets for the NLC (therefore one needs to know how many magnets, and of what kind, will be used in the NLC).

Availability of a system of N similar components = $(\text{Availability of one component})^N$

The large number of magnets that will exist in the ILC- many thousands of them, is what makes achieving a reasonable system availability so difficult. As you will see from the data below, the system of NLC magnets would not have reached the 97.5% availability specification (that was suggested in the NLC ZDR) if we would not have improved their individual availabilities over what we achieved with SLAC magnets. The NLC magnet power supply system would meet the 97.5% availability specification if all 3382 of its large PS were used in a redundant mode.

Average SLAC avail for a single item	Solid wire magnet	Water cooled magnet	Small switching PS	Large switching PS	
	0.999999465	0.999991271	0.9999957	0.9999814	
No. of items in NLC	2202	4965	2785	3382	All redundant
Predicted NLC system availability*	0.9988	0.9576	0.9881	0.9392	0.9975

*predict availabilities for the NLC if no effort is made to improve the quoted SLAC measured availabilities.

These four published papers, available on SLAC's website as indicated, describe the work we have done at SLAC to improve the reliability of future magnets; the Failure Modes and Effects Analysis (FMEA) technique and how we used it to change our magnet designs and to cost the failures over a 30 year lifetime of various systems.

This paper describes FMEA and how we used it at SLAC to redesign a standard SLAC magnet:
"A Novel Approach to Increasing the Reliability of Accelerator Magnets"
http://www.slac.stanford.edu/pubs/slacpubs/8000/slac-pub-8254.html

This paper describes the fabrication and testing of the redesigned quadrupole:
"High Reliability Prototype Quadrupole for the Next Linear Collider"
http://www.slac.stanford.edu/pubs/slacpubs/8000/slac-pub-8990.html

This paper describes an extension of the FMEA technique to help make the choices for what to spend money on in trying to improve the reliability of a system:
"Cost Based Failure Modes and Effects Analysis (FMEA) for Systems of Accelerator Magnets"
http://www.slac.stanford.edu/pubs/slacpubs/9000/slac-pub-9913.html

"Comparison Study of Electromagnet and Permanent Magnet Systems for an Accelerator Using Cost-Based Failure Modes and Effects Analysis"
http://www.slac.stanford.edu/pubs/slacpubs/10000/slac-pub-10207.html

I am available to talk to anyone further about all of the above work, you can reach me via e-mail at cherrill@slac.stanford.edu or by phone at USA-650-926-3474.